

# Evidence for $\eta_c \rightarrow \gamma\gamma$ and Measurement of $J/\psi \rightarrow 3\gamma$

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The decay of  $J/\psi$  to three photons is studied using  $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$  in a sample of 106 million  $\psi(3686)$  events collected with the BESIII detector. First evidence of the decay  $\eta_c \rightarrow \gamma\gamma$  is reported, and the product branching fraction is determined to be  $\mathcal{B}_{J/\psi \rightarrow \gamma\eta_c, \eta_c \rightarrow \gamma\gamma} = (4.5 \pm 1.2 \pm 0.6) \times 10^{-6}$ , where the first error is statistical and the second systematic. The branching ratio for the direct decay is  $\mathcal{B}_{J/\psi \rightarrow 3\gamma} = (11.3 \pm 1.8 \pm 2.0) \times 10^{-6}$ .

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Decays of positronium to multi-photons are regarded as an ideal test-bed for QED [1]. The analogous processes in charmonia act as a probe of the strong interaction [2]. For example, the decays of  $\eta_c \rightarrow \gamma\gamma$  and  $J/\psi \rightarrow 3\gamma$  have relatively simple theoretical descriptions, and their measurements allow for fundamental tests of non-perturbative QCD theory [3]. One key parameter, which influences the predictive capability of QCD models, is the value of the running coupling constant [4]. In principle, the ratios of  $\mathcal{B}_{J/\psi \rightarrow 3\gamma}/\mathcal{B}_{J/\psi \rightarrow ee}$  and  $\mathcal{B}_{\eta_c \rightarrow \gamma\gamma}/\mathcal{B}_{J/\psi \rightarrow ee}$ , where  $\mathcal{B}_{J/\psi \rightarrow ee}$  has been precisely measured [6], provide a clean way to extract the running coupling constant [5]. Here,  $\mathcal{B}_X$  denotes the branching fraction of the decay X.

With the exception of the CLEO-c measurement of  $\mathcal{B}_{J/\psi \rightarrow 3\gamma} = (12 \pm 3 \pm 2) \times 10^{-6}$  [7], not much is known experimentally about the decays of the  $J/\psi$  to three photons.  $\mathcal{B}_{\eta_c \rightarrow \gamma\gamma}$  is determined mainly from two-photon fusion  $\gamma\gamma^{(*)} \rightarrow \eta_c$  [6], because direct measurements of the decay have low statistics. The latest measurement from CLEO-c gave  $\mathcal{B}_{J/\psi \rightarrow \gamma\eta_c, \eta_c \rightarrow \gamma\gamma} = (1.2^{+2.7}_{-1.1} \pm 0.3) \times 10^{-6}$  or an upper limit of  $6 \times 10^{-6}$  at the 90% confidence level [7]. Ignoring the higher-order QCD corrections, the branch-

ing fraction of  $J/\psi \rightarrow \gamma\eta_c, \eta_c \rightarrow \gamma\gamma$  is predicted to be  $(4.4 \pm 1.1) \times 10^{-6}$  [8].

This letter presents the first evidence for  $\eta_c \rightarrow \gamma\gamma$  in the three photon decay of the  $J/\psi$  via  $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$ . In addition, the branching fraction of  $J/\psi \rightarrow 3\gamma$  is measured with improved precision. The analysis is based on a sample of  $(1.06 \pm 0.04) \times 10^8$   $\psi(3686)$  events [9] collected in the Beijing Spectrometer (BESIII) operating in the Beijing Electron-Positron Collider (BEPCII) [10]. Using  $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$  events for this study rather than  $e^+e^- \rightarrow J/\psi \rightarrow 3\gamma$  eliminates background from the QED process  $e^+e^- \rightarrow 3\gamma$ .

The upgraded BEPCII is designed with a double-ring structure. The BESIII detector [10] is a cylindrically symmetric detector with five sub-detector components, that are from inside to out: a main drift chamber (MDC), a time-of-flight (TOF) system, an electromagnetic calorimeter (EMC), a super-conducting solenoid magnet, and a muon chamber. The momentum resolution for charged tracks reconstructed by the MDC is 0.5% for transverse momenta of 1 GeV/c. The energy resolution for deposited showers in the EMC is 2.5% for 1 GeV photons.

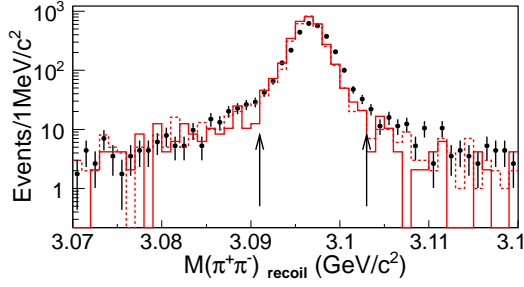


FIG. 1. Distributions of mass recoiling against  $\pi^+\pi^-$ ,  $M(\pi^+\pi^-)_{\text{recoil}}$ , in data (points), MC simulation of the process  $J/\psi \rightarrow \gamma(\gamma\gamma)\eta$  (solid line), and MC  $\psi(3686)$  inclusive decays (dashed line). The arrows indicate the region to select  $J/\psi$  events. This comparison is based on a selected sample of  $J/\psi \rightarrow \gamma\eta \rightarrow 3\gamma$ .

The BESIII detector is modeled with a Monte Carlo (MC) simulation based on GEANT4 [11, 12]. KKMC [13] is used to generate MC samples at any specified energy, taking into account the initial state radiation and the beam energy spread. The  $\psi(3686)$  decays are generated with the generator EVTGEN [14] for known decay modes according to their branching fractions as listed by the Particle Data Group (PDG) [6], and with Lundcharm [15] for unknown  $\psi(3686)$  decay modes.

For the selection of  $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$ ,  $J/\psi \rightarrow 3\gamma$  candidates, events with only two charged tracks and at least three photons are required. Minimum distances of charged tracks to the interaction point (IP) are required to be within 10 cm in the beam direction and within 1 cm in the perpendicular plane. The two charged tracks are assumed to be  $\pi^+\pi^-$  candidates, and the mass recoiling against them in the center of mass system must be within  $[3.091, 3.103] \text{ GeV}/c^2$ , as shown in Fig. 1.

Photon candidates are chosen from isolated clusters in the EMC whose energies are larger than 25 MeV in the barrel region ( $|\cos\theta| < 0.8$ ) and 50 MeV in the end-cap regions ( $0.86 < |\cos\theta| < 0.92$ ). Here,  $\theta$  is the polar angle with respect to the beam direction. To reject photons from bremsstrahlung and from interactions with material, showers within a cone angle of  $5^\circ$  around the momenta of charged tracks are rejected. Reconstructed showers due to electronic noise or beam backgrounds are suppressed by limiting the timing information within  $[0, 700] \text{ ns}$  after the event start time.

The  $\pi^+$  and  $\pi^-$  tracks are fit to a common vertex to determine the event IP, and a four constraint kinematic fit to the initial four-momentum of the  $\psi(3686)$  is applied for each  $\pi^+\pi^-\gamma\gamma\gamma$  combination. The combination with the smallest fit chisquare,  $\chi^2_{4C}$ , is kept, and  $\chi^2_{4C} < 50$  is required.

Distributions of  $M(\gamma\gamma)_{\text{lg}}$  versus  $M(\gamma\gamma)_{\text{sm}}$  are shown in Fig. 2, where  $M(\gamma\gamma)_{\text{lg}}$  and  $M(\gamma\gamma)_{\text{sm}}$  are the largest and smallest two-photon invariant masses among the three combinations, respectively. Events from the background processes  $J/\psi \rightarrow \gamma\pi^0/\eta/\eta' \rightarrow 3\gamma$  are clearly seen within the three vertical bands. These backgrounds

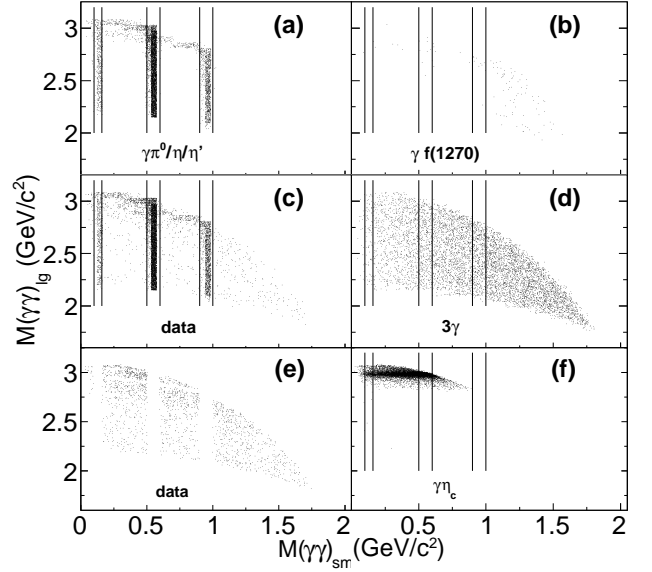


FIG. 2. Scatter plots of  $M(\gamma\gamma)_{\text{lg}}$  versus  $M(\gamma\gamma)_{\text{sm}}$  for (c) data and for MC simulations of the processes (a)  $J/\psi \rightarrow \gamma\pi^0/\eta/\eta' \rightarrow 3\gamma$ , (b)  $J/\psi \rightarrow \gamma f(1270) \rightarrow \gamma(\gamma\gamma)\pi^0(\gamma\gamma)\pi^0$ , (d)  $J/\psi \rightarrow 3\gamma$ , and (f)  $J/\psi \rightarrow \gamma\eta_c \rightarrow 3\gamma$ . Compared with plot (c), plot (e) shows the distribution of data after excluding backgrounds from  $J/\psi \rightarrow \gamma\pi^0/\eta/\eta'$ , where the empty bands are due to the requirements on any two-photon combination. The vertical lines indicate the mass windows to reject  $\pi^0$ ,  $\eta$  and  $\eta'$ .

are suppressed by removing all the events where the invariant mass of any two photons,  $M(\gamma\gamma)$ , lies in the mass windows  $[0.10, 0.16] \text{ GeV}/c^2$ ,  $[0.50, 0.60] \text{ GeV}/c^2$ , or  $[0.90, 1.00] \text{ GeV}/c^2$ . Background events which lie outside these mass windows are estimated based on MC simulation.

Events from  $J/\psi \rightarrow \gamma e^+e^-$  also contribute to the background, when electron-positron tracks fail to be reconstructed in the MDC and the associated EMC clusters are thus identified as photon candidates. To reject this background, the total number of hits in the MDC within an opening angle of five EMC crystals around the centers of three photon showers is required to be less than 40.

$J/\psi \rightarrow \gamma\pi^0\pi^0$  events can pass the selection requirements if the two photons from one of the  $\pi^0$  decays are nearly collinear or when one of the  $\pi^0$ s is very soft. Due to the large  $\gamma\pi^0\pi^0$  branching fraction, these events are a major source of background. In order to model this background, the rich structure of intermediate resonance must be taken into account. Hence, a partial wave analysis (PWA) [16] was performed on the BESIII  $J/\psi$  data, following the procedures described in Ref. [18]. Figure 3 shows excellent agreement between data and MC simulation based on the PWA results. Decays of  $J/\psi \rightarrow \gamma f_J$ ,  $f_J \rightarrow \gamma\gamma$  are negligible because of their extremely small branching fractions [6].

The  $\chi^2_{4C}$  value can be used to separate  $3\gamma$  and  $\gamma\pi^0\pi^0$  final states, and the  $M(\gamma\gamma)_{\text{lg}}$  distribution can be used to distinguish  $J/\psi \rightarrow \gamma(\gamma\gamma)\eta_c$  from the direct process

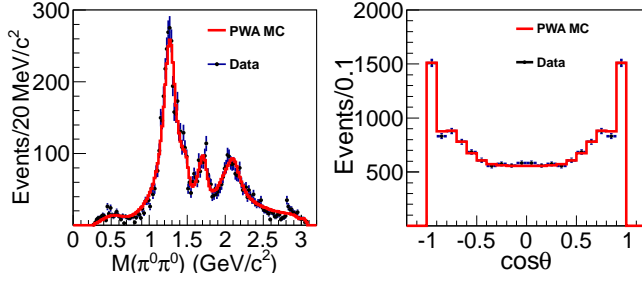


FIG. 3. Distributions of invariant mass of  $\pi^0\pi^0$  (left) and polar angle of  $\pi^0$  (right) in a control sample of  $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$ ,  $J/\psi \rightarrow \gamma\pi^0\pi^0$ . Points with error bars are data and solid lines MC simulation.

$J/\psi \rightarrow 3\gamma$ . Therefore, a two-dimensional maximum likelihood fit is performed on the  $M(\gamma\gamma)_{\text{lg}}$  and  $\chi^2_{4C}$  distributions to estimate the yields of  $J/\psi \rightarrow 3\gamma$  and  $J/\psi \rightarrow \gamma(\gamma\gamma)_{\eta_c}$ . The projections of the two-dimensional fit results are shown in Fig. 4 and the numerical results listed in Table I. The  $\chi^2$  per degree of freedom corresponding to the fit is 318/349. For the fit, the shapes of both signal and background processes are taken from MC simulation; the normalization of  $J/\psi \rightarrow \gamma(\gamma\gamma)_{\pi^0/\eta/\eta'}$  is fixed to the expected density based on MC simulation; and the normalization of  $J/\psi \rightarrow \gamma\pi^0\pi^0$  is allowed to float. Backgrounds of non- $J/\psi$  decays are estimated using the  $M(\pi^+\pi^-)_{\text{recoil}}$  sidebands within  $[2.994, 3.000]$   $\text{GeV}/c^2$  and  $[3.200, 3.206]$   $\text{GeV}/c^2$ . The statistical significance of  $J/\psi \rightarrow 3\gamma$  ( $J/\psi \rightarrow \gamma(\gamma\gamma)_{\eta_c}$ ) is  $8.3\sigma$  ( $4.1\sigma$ ), as determined by the ratio of the maximum likelihood value and the likelihood value for a fit under the null hypothesis. When the systematic uncertainties are included, the significance becomes  $7.3\sigma$  ( $3.7\sigma$ ). The branching fraction is calculated using  $\mathcal{B} = \frac{n_{\text{obs}}}{N_{\psi(3686)} \times \mathcal{B}_{\psi(3686) \rightarrow \pi^+\pi^-J/\psi} \times \epsilon}$ , where  $n_{\text{obs}}$  is the observed number of events,  $N_{\psi(3686)}$  is the number of  $\psi(3686)$  events [9], and  $\epsilon$  the detection efficiency.  $\mathcal{B}_{\psi(3686) \rightarrow \pi^+\pi^-J/\psi}$  is taken from the PDG [6].

Many sources of systematic error are considered. Simulation of direct  $J/\psi \rightarrow 3\gamma$  assumes the lowest order matrix element to be similar to the decay of orthopositronium to three photons [17]. The systematic uncertainty in the detection efficiency is estimated by weighting the efficiencies in the Dalitz-like plot of Fig. 2(d) by the experimental data. The maximum relative change is 15%.

The invariant mass of  $\eta_c$  in the  $J/\psi \rightarrow \gamma\eta_c$  decay is assumed to have a relativistic Breit-Wigner distribution, weighted by a factor of  $E_\gamma^3$  multiplied by a damping factor  $e^{-E_\gamma^2/8\beta^2}$  with  $\beta = (65.0 \pm 2.5) \text{ MeV}$  [19]. Here  $E_\gamma^*$  is the energy of the radiated photon in the  $J/\psi$  rest frame. An alternative parametrization of the damping factor used by KEDR [20], as well as variations of the  $\eta_c$  width in the range 22.7–32.7 MeV, are used to determine the systematic uncertainties.

The systematic uncertainty due to possible differences between MC and data is evaluated by performing the

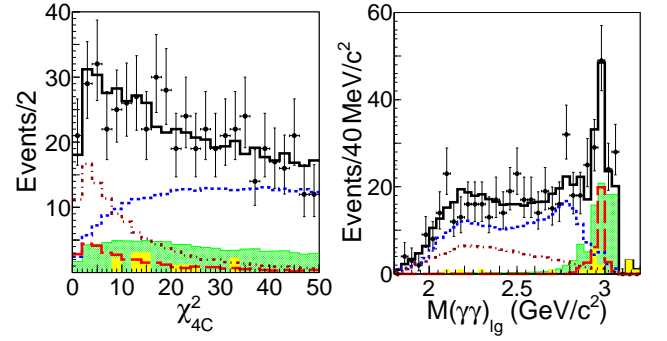


FIG. 4. (color online) Projection plots of the two-dimensional fit to  $\chi^2_{4C}$  (left) and  $M(\gamma\gamma)_{\text{lg}}$  (right). Here points with error bars are data and the solid line is the fit to data. The dotted-dash line shows the contributions of  $J/\psi \rightarrow 3\gamma$  (dark red), the long-dash line  $J/\psi \rightarrow \gamma\eta_c \rightarrow 3\gamma$  (red), and the dotted line  $J/\psi \rightarrow \gamma\pi^0\pi^0$  (blue). The shaded histogram represents the backgrounds from  $J/\psi \rightarrow \gamma\pi^0/\eta/\eta'$  (green) and the solid line non- $J/\psi$  decays (yellow).

TABLE I. The detection efficiency  $\epsilon$ , the signal yields, the estimated significance, and the measured branching fractions with the errors for the two decay modes. The first errors are statistical and the second systematic. Values of the significance outside the parenthesis are statistical only and those within the parenthesis include systematic effects.

modes	$J/\psi \rightarrow 3\gamma$	$J/\psi \rightarrow \gamma\eta_c \rightarrow 3\gamma$
$\epsilon$ (%)	$27.9 \pm 0.1$	$20.7 \pm 0.2$
yields	$113.4 \pm 18.1$	$33.2 \pm 9.5$
significance	$8.3(7.3)\sigma$	$4.1(3.7)\sigma$
$\mathcal{B}(\times 10^{-6})$	$11.3 \pm 1.8 \pm 2.0$	$4.5 \pm 1.2 \pm 0.6$

two-dimensional fit of the  $\chi^2_{4C}$  and  $M(\gamma\gamma)_{\text{lg}}$  distributions with the MC shapes smeared with an asymmetric Gaussian function, the parameters of which are determined by comparing a control data sample of  $J/\psi \rightarrow \gamma\eta$ ,  $\eta \rightarrow \gamma\gamma$  to MC simulation. This function serves to adjust the detector resolution in the MC simulation to data.

The efficiency of the mass window requirement around the  $J/\psi$  resonance in the  $M(\pi^+\pi^-)_{\text{recoil}}$  spectrum, which is sensitive to the tracking efficiency of low momentum pions, is studied with a  $J/\psi \rightarrow \gamma\eta$ ,  $\eta \rightarrow \gamma\gamma$  control sample. The systematic uncertainty in the expected number of background events from  $J/\psi \rightarrow \gamma\pi^0(\eta, \eta')$  was evaluated by varying their branching fractions by one standard deviation [6].

It has been verified that the  $\chi^2_{4C}$  distribution of the  $\gamma\pi^0\pi^0$  final states does not depend on the components of the intermediate processes involved, *i.e.*, mainly the  $f_J$  states [7]. However, the  $M(\gamma\gamma)_{\text{lg}}$  distribution does, and good understanding of the primary components via PWA is needed. Information about the amplitudes in  $J/\psi \rightarrow \gamma\pi^0\pi^0$  from the previous BESII analysis [16] is also used in the simulation as an additional check; the relative changes in the results are taken as systematic uncertainties.

The photon detection efficiency is studied with dif-



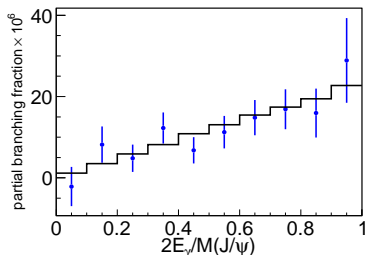


FIG. 5. The energy spectrum in the  $J/\psi$  rest frame of inclusive photons in  $J/\psi \rightarrow 3\gamma$ . The points with error bars are the partial branching fractions as a function of the ratio  $2E_\gamma/M_{J/\psi}$  measured in data. Here  $E_\gamma$  is the photon energy and  $M_{J/\psi}$  is the  $J/\psi$  mass. The solid line is the theoretical calculation according to the ortho-positronium decay formula [17].

TABLE II. Summary of the relative systematic uncertainties. A dash (–) means the uncertainty is negligible.

sources	uncertainties (%)	
	$\mathcal{B}_{J/\psi \rightarrow 3\gamma}$	$\mathcal{B}_{J/\psi \rightarrow \gamma\eta_c \rightarrow 3\gamma}$
signal model	15	–
$\eta_c$ width	–	5
$\eta_c$ line shape	1	1
resolution	3	9
$M(\pi^+\pi^-)_{\text{recoil}}$ window	4	4
$\pi^0, \eta, \eta'$ rejection	0.5	5
PWA model	2	2
photon detection	3	3
tracking	2	2
number of good photons	0.5	0.5
kinematic fit and $\chi^2_{4C}$ requirement	2	2
fitting	5	5
number of $\psi(3686)$	4	4
$\mathcal{B}_{\psi(3686) \rightarrow \pi^+\pi^- J/\psi}$	1.2	1.2
total	18	15

ferent control samples, such as radiative Bhabha and  $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$ ,  $J/\psi \rightarrow \rho^0\pi^0$  [21]. The MDC tracking efficiency is studied using selected samples of  $J/\psi \rightarrow \rho\pi$  and  $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$ ,  $J/\psi \rightarrow \pi^+\pi^- p\bar{p}$  [18]. Samples of  $J/\psi \rightarrow \gamma\eta$ ,  $\eta \rightarrow \gamma\gamma$  are selected to study the uncertainties arising from requirements on the number of photon candidates and the  $\chi^2_{4C}$  requirement. The uncertainty due to the fitting is evaluated by changing the fitting range and the bin width.

The energy spectrum of inclusive photons in  $J/\psi \rightarrow 3\gamma$  provides information on the internal structure of the  $J/\psi$  [5]. The inclusive photon is defined as any one of the three photons in the final state. Partial branching fractions were measured as a function of inclusive photon energy  $E_\gamma$  in the  $J/\psi$  rest frame. This model-independent distribution is illustrated in Fig. 5, where all three photons are plotted and the error bars are combinations of the statistical and systematic uncertainties. The distribution agrees well with the theoretical calculation adapted from the ortho-positronium decay model.

In conclusion, the  $J/\psi$  decays to three photons are studied using  $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$  decays at BESIII. First evidence of the  $\eta_c \rightarrow \gamma\gamma$  decay is reported, and the product branching fraction of  $J/\psi \rightarrow \gamma\eta_c$  and  $\eta_c \rightarrow \gamma\gamma$  is determined to be  $\mathcal{B}_{J/\psi \rightarrow \gamma\eta_c, \eta_c \rightarrow \gamma\gamma} = (4.5 \pm 1.2 \pm 0.6) \times 10^{-6}$ . This result is consistent with the theoretical prediction [8] and CLEO-c's result [7]. When combined with the input of  $\mathcal{B}_{J/\psi \rightarrow \gamma\eta_c} = (1.7 \pm 0.4) \times 10^{-2}$  from the PDG [6], we obtain  $\mathcal{B}_{\eta_c \rightarrow \gamma\gamma} = (2.6 \pm 0.7 \pm 0.7) \times 10^{-4}$ , which agrees with the result from two-photon fusion [6]. The direct decay of  $J/\psi \rightarrow 3\gamma$  is measured to be  $\mathcal{B}_{J/\psi \rightarrow 3\gamma} = (11.3 \pm 1.8 \pm 2.0) \times 10^{-6}$ , which is consistent with CLEO-c's result. Considering the ratio of  $\mathcal{B}_{J/\psi \rightarrow 3\gamma}/\mathcal{B}_{J/\psi \rightarrow ee}$  at the first order of QCD correction, the running coupling constant at the  $J/\psi$  nominal mass scale can be extracted. The energy spectrum of inclusive photon is also measured.

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[1] S. G. Karshenboim, Int. J. Mod. Phys. A **19**, 3879 (2004); S. Asai, Y. Kataoka, T. Kobayashi *et al.*, AIP Conf. Proc. **1037**, 43 (2008).  
[2] A. Czarnecki and K. Melnikov, Phys. Lett. B **519**, 212 (2001).

[3] K. Hagiwara, C. B. Kim and T. Yoshino, Nucl. Phys. B **177**, 461 (1981).  
[4] R. Barbieri, E. d'Emilio, G. Curci and E. Remiddi, Nucl. Phys. B **154**, 535 (1979); M. Beneke, A. Signer and V. A. Smirnov, Phys. Rev. Lett. **80**, 2535 (1998);

- G. T. Bodwin and A. Petrelli, Phys. Rev. D **66**, 094011 (2002).
- [5] M. B. Voloshin, Prog. Part. Nucl. Phys. **61**, 455 (2008); A. Petrelli, M. Cacciari, M. Greco *et al.*, Nucl. Phys. B **514**, 245 (1998).
- [6] J. Beringer *et al.* [Particle Data Group], Phys. Rev. D **86**, 010001 (2012).
- [7] G. S. Adams *et al.* [CLEO Collaboration], Phys. Rev. Lett. **101**, 101801 (2008).
- [8] W. Kwong, P. B. Mackenzie, R. Rosenfeld and J. L. Rosner, Phys. Rev. D **37**, 3210 (1988); A. Czarnecki and K. Melnikov, Phys. Lett. B **519**, 212 (2001).
- [9] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **81**, 052005 (2010).
- [10] M. Ablikim *et al.* [BESIII Collaboration], Nucl. Instrum. Meth. A **614**, 345 (2010).
- [11] S. Agostinelli *et al.* [GEANT Collaboration], Nucl. Instrum. Meth. A **506**, 250 (2003); J. Allison *et al.*, IEEE Trans. Nucl. Sci. **53**, 270 (2006).
- [12] Z. Y. Deng *et al.*, Chinese Physics C **30**, 371 (2006).
- [13] S. Jadach, B. F. L. Ward and Z. Was, Phys. Rev. D **63**, 113009 (2001).
- [14] R. G. Ping, Chinese Physics C **32**, 599 (2008).
- [15] J. C. Chen *et al.*, Phys. Rev. D **62**, 034003 (2000).
- [16] M. Ablikim *et al.* [BESIII Collaboration], Phys. Lett. B **642**, 441 (2006).
- [17] G. S. Adkins, Phys. Rev. Lett. **76**, 4903 (1996).
- [18] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **106**, 072002 (2011).
- [19] R. E. Mitchell *et al.* [CLEO Collaboration], Phys. Rev. Lett. **102**, 011801 (2009) [Erratum-ibid. **106**, 159903 (2011)].
- [20] V. V. Anashin *et al.*, arXiv:1012.1694 [hep-ex].
- [21] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **104**, 132002 (2010).